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ORIGINAL PAPER

Breathing dirty air, struggling in school: The case of air pollution and Student Learning in Chile

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Abstract
Air pollution has been linked to various health problems in children, including respiratory and neurological issues. Existing research has also found that exposure to air pollution can affect children's cognitive ability and academic performance, with some studies showing a decrease in test scores and grade point averages associated with increased exposure to hazardous air pollution. This study examined the association between air pollution and children's academic performance in Chile. This research addressed a critical gap in the literature by providing data from an understudied context and tracking children's academic performance at an individual level over time. We constructed a panel dataset that followed students from 1st to 8th grade and estimated their exposure to $PM_{2.5}$, based on the distance of their school to air monitoring stations from elementary to middle school. We tracked students' academic performance using a longitudinal fixed-effects regression model to assess the relationship between their grade point average (GPA) and air pollution. The results revealed that, on average, an increase in the percentage of days exceeding different official air quality standards significantly affected students' annual GPA. The study also showed that academic performance among students from families with lower economic resources is disproportionately affected by air pollution. The findings underscore the pressing issue of environmental justice, highlighting that numerous students attend schools in the unhealthy environments of several Chilean cities that frequently bear the burden of socioeconomic disadvantage.

Keywords Air pollution · Particulate matter · Academic performance · Schools · Fixed effects regression · Longitudinal design

Introduction

Air pollution is the single most significant environmental cause of disease and premature death (Landrigan et al., 2018), contributing to an estimated 8 million premature deaths per year worldwide (Burnett et al., 2018)—15 times more deaths than

Extended author information available on the last page of the article from all wars and other forms of violence (Landrigan et al., 2018). While a large body of literature has shown that air pollution harms human health, its social consequences have been less studied (Lu, 2020). In recent years, research has linked health problems produced by air pollution to academic results (Amanzadeh et al., 2020; Bensnes, 2015; Ebenstein et al., 2016; Gaffron & Niemeier, 2015; Grineski et al., 2013, 2016, 2020; Kweon et al., 2018; London et al., 2016; Miller & Vela, 2013). This impact on students can have long-lasting consequences, especially if critical air quality episodes occur during exam times. Hence, the correlation between air quality and academic performance may have immediate and lasting implications that are typically overlooked when evaluating the benefits and drawbacks of air quality control efforts in southern Chile.

Prior studies have shown that environmental changes like increased particulate matter can affect students' academic performance in different ways. However, the robustness of current evidence regarding the impact of air pollution on academic performance can be enhanced. Although existing research offers valuable insights, it is geographically limited and often relies on cross-sectional designs or studies with constrained temporal or regional scope (Stenson et al., 2021). This study expands the existing body of research by examining the correlation between air pollution and children's academic performance in Chile, a context that has been largely overlooked in the literature. While much of the research on the impact of pollution on academic performance has been conducted in the Global North, particularly in the United States, this study provides valuable insights from the Global South.[1] By focusing on Chile, we address a critical gap in the literature and contribute to a more comprehensive understanding of the global implications of environmental pollution on educational outcomes. The diverse environmental and socio-economic conditions across Chilean cities present a unique opportunity to examine the relationship between air pollution and academic performance in different contexts. This variability is a critical strength of our study, as it allows us to assess how these dynamics influence educational outcomes across regions with differing levels of pollution, economic development, and access to resources. Exploring this variability enables us to provide layered insights into how air pollution impacts students in both more affluent urban centers and less developed areas, thereby offering a comprehensive understanding of the issue. We used a longitudinal fixed effects regression model to assess the relationships between air pollution and students' academic performance, measured by the grade point average (GPA), while controlling for potentially important time-invariant factors.

[1] We adopt Pellow's (2007) conceptualization of the Global North and Global South as social constructs rather than strictly geographical ones. The Global North is characterized by more privileged, affluent Communities, often associated with the 'developed' or 'first' world. In contrast, the Global South refers to politically and economically marginalized communities or nations, typically linked to the 'developing' world.

Literature review

Extensive scientific research shows that children are more physiologically susceptible to the detrimental effects of air pollution than adults (Bertoldi et al., 2012; Brugha & Grigg, 2014), and exposure to environmental toxicants can harm their rapidly developing respiratory and neurological systems (Guxens & Sunyer, 2012; Schwartz, 2004). Furthermore, children spend more time outdoors than adults and breathe in more polluted air relative to their weight (Antipova, 2020). Epidemiological studies have shown that poor air quality has various adverse effects on children's health, ranging from the exacerbation of asthma or other respiratory diseases (Grineski et al., 2013; Neidell, 2004; Patel & Miller, 2009) to childhood cancer (Filippini et al., 2019; Lavigne et al., 2017; Seifi et al., 2019). Even the mother's exposure to high levels of pollution during pregnancy can affect different evolutionary stages, causing, for example, lower birth weight (Lavigne et al., 2016; Olsson et al., 2013), autism (Ornoy et al., 2015), or motor or cognitive function development issues (Lertxundi et al., 2019).

Research on the relationship between air pollution and school performance has examined the effects of both in utero and contemporaneous exposures. The methodological strategies for the former tend to relate birth records to the test scores or survey results of individuals later in life (Almond et al., 2007; Bharadwaj et al., 2014; Sanders, 2012). For example, Bharadwaj et al. (2014) found that variation in carbon monoxide exposure among pregnant women in Santiago, Chile, affects 4th-grade test scores in their children. Sanders (2012) examined how the decrease in total suspended particulates induced by the industrial recession in the 1980s impacts high school exam performance in Texas. The analysis shows that a standard deviation decrease in the mean pollution level of the birth year is linked to a 1.9% standard deviation increase in test scores.

Research conducted in the Global North, primarily in the United States, shows that there are two potential mechanisms by which air pollution exposure may affect children's school performance contemporaneously. First, poor air quality can directly affect students' cognitive abilities. An emerging line of research quantifies the harmful effects of bad air quality on children's cognitive functioning, given that neuroinflammation is produced when pollutants enter the body (Brockmeyer & D'Angiulli, 2016; Calderón-Garcidueñas et al., 2016, 2019; Davis et al., 2019; Rivas et al., 2019). This process contributes to cell loss within the central nervous system, causing deficits in cognitive function that can affect a child's ability to perform well on tests. In the social sciences, applied econometric research has explored the possible relationship between exposure to hazardous air pollution and academic performance (Bensnes, 2015; Ebenstein et al., 2016; Grineski et al., 2016; Marcotte, 2017; Miller & Vela, 2013). Marcotte (2017), for example, found that between the ages of five and eight, students scored up to 2% lower on math and reading tests on days with high pollen levels or $PM_{2.5}$ than on days when levels were low. Similarly, Grineski et al. (2016) observed a decrease between 0.11 and 0.40 in individual students' grade point averages (GPA) associated with an interquartile range increase in hazardous air pollution exposure. Using a fixed effects regression model, Bensnes (2015) found that a one standard deviation increase in pollen decreased the average students' score by about 2.5% of the standard deviation in a Norwegian high school sample. In countries with less-developed economies, lack of quality data has made research in this area difficult; however, some reports are worth noting. In one study conducted in the metropolitan region of Santiago, Chile, Miller and Vela (2013) found a statistically significant decline in school exam performance during years when PM_{10} levels were high. More recently, Amanzadeh et al. (2020) quantified the impact of short-term exposure to particulate matter (PM_{10} and $PM_{2.5}$) on test performance in the two largest cities in Iran: Tehran and Mashhad. Their results showed a robust and significant negative relationship between PM concentration and test performance.

Additionally, air pollution can increase the likelihood of respiratory ailments, which can jeopardize a student's academic performance. Several studies have found a direct correlation between the proximity of schools to industrial pollution or major roadways with high traffic density and an increase in ill health effects on children, which could affect their performance (Amram et al., 2011; Park & Jo, 2004; Sánchez-Guerra et al., 2012; Wilhelm et al., 2007). The persistence of asthma, for example, is linked to lower academic performance (Grineski et al., 2016), either because the condition temporarily limits students' ability to take tests (Moonie et al., 2008) or because it increases absenteeism (Currie et al., 2009; Mohai et al., 2011). Currie et al. (2009) described patterns of school absenteeism in Texas. Their study showed that absenteeism increases when there are high levels of carbon monoxide and particulate matter in the environment. A study conducted in Michigan revealed that schools situated closer to significant highways recorded the lowest attendance rates, which served as an indication of suboptimal health, and boasted the highest percentage of students who were unable to fulfill the state's educational testing standards (Kweon et al., 2018; Mohai et al., 2011). The authors showed that this relationship was significant even after controlling for school district expenditures, school size, student–teacher ratio, free lunch enrollment, and other contextual factors (Kweon et al., 2018).

While this body of research provides important insights, most studies have focused on high-income nations, leaving a significant gap in our understanding of how air pollution affects academic performance in countries from the Global South. The extent to which relationships found in the Global North translate into regions characterized by enduring challenges of access to formal housing, informality, and socioeconomic inequality remains uncertain. Prior studies conducted in Chile have primarily focused on urban areas, particularly the capital, Santiago, without accounting for the broader regional dynamics influencing the relationship between air pollution and educational achievement. In Latin American countries, air quality monitoring initiatives were started in the 1980s in response to escalating levels of air pollution in major urban centers across several countries in the region, as documented by Romieu et al. (1992). These programs have been relatively successful in capitals such as Buenos Aires (Argentina), Santiago (Chile), and Mexico City. However, pollution problems have emerged in smaller cities that are less able to invest in mitigation policies and tend to be less studied. Through our research, we attempt to fill this knowledge gap by examining how disparities in extended exposure to environmental hazards can give rise to educational inequality in children's development.

We also extend the literature in this area methodologically. Most prior studies have been conducted at the school level, indicating that attending schools in more polluted areas worsens children's aggregate standardized academic scores (Gaffron & Niemeier, 2015; Kweon et al., 2018; Legot et al., 2012; London et al., 2016; Miller & Vela, 2013; Mohai et al., 2011; Pastor et al., 2004; Rosofsky et al., 2014; Zweig et al., 2009). Although these studies establish correlations between pollution levels in schools and aggregate standardized test scores, it is important to note that the conclusions drawn from group-level data should not be applied to draw individual-level conclusions (Beale et al., 2008). Despite their merits, studies conducted at the school level have problems identifying causal effects because of the influence of several potentially confounding factors. Several studies have shown how different individual sociodemographic determinants, such as the mother's level of education (Hofflinger & Boso, 2021; Magnuson, 2007), the parents' ethnic origin (Duncan & Magnuson, 2005), or socioeconomic status (SES) influence a child's grades. On many occasions, geographic differences in pollution levels are correlated with school or family characteristics, which may also be related to academic performance. For example, air pollution tends to be higher where low-income families live, and low-income children may be more likely to score poorly on math or reading tests. Most studies on air pollution and academic performance at the individual level are cross-sectional, thereby making it difficult to estimate changes over time (Stenson et al., 2021). Our study contributes to growing attempts to overcome these problems by applying a longitudinal design (Grineski et al., 2016; Marcotte, 2017; Shier et al., 2019; Stingone et al., 2017). Using a unique database in this area of study, we follow a cohort of students through the most critical years of their schooling to observe the impact of air pollution on their academic performance, while controlling for the effects of other potential individual- and school-level covariates. In addition to the advantages that this research design offers over most previous studies, the case of Chile allows us to broaden the geographical scope of this research to include countries in the Global South.

Data and methods

Study area

We used information about $PM_{2.5}$ from 12 monitoring stations; eight were in the urban area of the capital city of Santiago (Metropolitan region and Talagante), and the remainder were distributed from north to south in the cities of Rancagua (VI region), Temuco (IX region), Valdivia (XIV region), and Osorno (X region). Each monitoring station was associated with a 2,000-m-wide school selection area (see Figure SM1 supplementary materials).

Data

We created a longitudinal dataset at the student level that included students' grades (annual GPA), attendance, and exposure to air pollution ($PM_{2.5}$) in 11 municipalities (school districts) in central and southern Chile. Using a unique identification number provided by the Ministry of Education, we followed 5,509 students from the 1st grade (2009) until they finished middle school (8th grade, 2016). To create a more comparable group regarding academic performance, we excluded students who failed a grade in elementary or middle school and those who dropped out or were transferred to another school.[2] To run a sensitivity analysis based on the distance between the schools and the monitoring stations, we selected schools within a radius of 800, 1200, 1500, and 2000 m from the monitoring stations. We assigned the annual level of exposure to air pollution of students in those schools and estimated whether the concentration of $PM_{2.5}$ impacted their annual attendance and GPA.

The air quality data comes from the National Air Quality Information System (*Sistema de Información Nacional de Calidad del Aire*, SINCA in Spanish). We collected information on the levels of air pollution ($PM_{2.5}$) from Cerro Navia, El Bosque, La Florida, Las Condes, Santiago, Pudahuel, Puente Alto, Talagante, Rancagua, Temuco, Padre Las Casas, Valdivia, and Osorno. These municipalities were selected based on two criteria. First, the cities implemented the Atmospheric Decontamination Plan, ADP (*Plan de Descontaminación Atmosférica* in Spanish), providing reliable and accurate information about air pollution. Second, these twelve municipalities are the only ones in Chile with complete data on air pollution for the study period (2009 to 2016). Most of the data provided by the SINCA were collected after 2009. We used data about $PM_{2.5}$ emissions during the fall and winter seasons, particularly 1 April to 30 September, because this is the period the ADP is implemented and is also consistent with the school year in Chile (March to December). The original dataset provides information every 30 min, but we collapsed the data to an annual $PM_{2.5}$ level to join with the student's annual attendance rates and grades.

The Ministry of Education provides data regarding student attendance and grades. Referred to as student performance, this data set (*rendimiento por estudiante* in Spanish) encompasses every student's attendance rate and grade point average (GPA) throughout the country. The dataset has a unique identification number for each school in which students were enrolled, and we used this number to link students' attendance, grades, and air pollution assigned to each school (based on the air quality monitoring system).

Finally, data on family income were obtained from the National Educational Quality Measurement System (SIMCE) in 2012 (4th grade). Family income is a categorical variable (15 bins); however, we transformed it to the midpoint of each

[2] It may be that exposure to air pollution is one factor, among others, that influences why some students fail a grade, drop out, or transfer to another school. In this case, our model may underestimate the relationship between air pollution and student achievement.

category using the harmonic mean of a Pareto distribution (von Hippel et al., 2017). Using this method, we converted family income into a numerical variable and estimated the income quartiles.

Method

We estimated the impact of air pollution on academic performance at the student level using a longitudinal fixed effects regression model. As mentioned above, we followed students from 1st to 8th grade; consequently, the dataset had eight observations (eight years) of each of the 5,509 students who participated in the study.

The models incorporated student-fixed effects to account for time-invariant individual attributes such as intelligence, motivation, and family characteristics. Furthermore, the models contain year fixed effects to control for the temporal patterns shared among students in each grade.

Our basic model was:

$$Y_{it} = \alpha_i + \beta_t + \gamma P_{ijt} + e_{it}$$

The dependent variable Y_{it} is the student's GPA (z-scores) i and year t, representing each grade (from 1st to 8th grade). In this case, α_i is a student fixed effect (dummy variable for each student), β_t is a year fixed effect (dummy variable for each grade), and e_{ijt} is an exogenous residual. γP_{ijt} represents the $PM_{2.5}$ concentration to which students i in school j and year t are exposed. We used seven independent variables: the annual average of $PM_{2.5}$, the World Health Organization (WHO (World Health Organization), 2005) (Percentage of days with $PM_{2.5}$ concentrations above 25 μg/m^3), the US Environmental Protection Agency (EPA (Environmental Protection Agency of the United States), 2024) (Percentage of days with $PM_{2.5}$ concentrations above 35 μg/m^3), and the Chilean Ministry of the Environment (MMA) (Percentage of days with $PM_{2.5}$ concentrations above 50 μg/m^3). These $PM_{2.5}$ limits correspond to the official standards when the children were exposed. In recent years, both the EPA and WHO have modified the exposure levels they consider healthy to make them stricter. We also included the percentage of days classified by the MMA as "alert," days with $PM_{2.5}$ concentrations between 80 and 109 μg/m3, "pre-emergency," days between 110 and 169 μg/m3, and the annual percentage of days above 170 μg/m3, which is classified as "emergency." We also included each student's annual attendance rate percentage as an independent variable, key to explaining students' annual GPA. To control for heteroscedasticity and within-student serial correlation in e_{it}, we clustered standard errors at the student level (Cameron & Miller, 2015).

We used a fixed effects model because it enabled us to effectively manage potential confounders, even though they were excluded in the model (Allison, 2009; Greene, 2011). The student-fixed effects controlled for omitted variables that did not vary over time, and the year-fixed effects controlled for time trends across grades. In this sense, since the model compares each student with themselves inside the same school over time, most individual, family, and school variables that impact the students' grades (such as intelligence, motivation, parents' education, and school culture, among others) are controlled by the fixed effects regression.

Results

Descriptive statistics are presented in Table 1, which shows the total observations and the mean, standard deviation, and minimum and maximum values of the variables used in the study. Although the annual GPA in Chile can range from 1 to 7, the lowest GPA to pass and be promoted to the next grade is 4. Furthermore, the average attendance rate of the participants was 93%. On average, from 1 April to 30 September, the concentration of $PM_{2.5}$ is above the international standards (WHO 25 µg/m3 and EPA 35 µg/m3) but below the Chilean threshold (50 µg/m^3). Furthermore, on average, on 28% of the days, the $PM_{2.5}$ concentrations were above the MMA threshold.

Figure SM2 shows the $PM_{2.5}$ concentration from 2009 to 2016. Most of the schools analyzed were exposed to high levels of air pollution during the fall and winter (see supplementary materials). On average, 5.3% of days from April to September were classified as an "alert," which is a day (24 h) with an average $PM_{2.5}$, a concentration between 80 and 109 µg/m^3, 3% as a "pre-emergency," and 1.4% as an "emergency."

We ran a fixed effect regression model at the student level to evaluate whether air pollution impacts students' annual GPA. The dependent variable was standardized (z-scores) to ensure the results were comparable to previous studies. We used seven different measured levels of $PM_{2.5}$ concentration: annual mean of $PM_{2.5}$, and percentage of days above the WHO, EPA, MMA, Alert, Pre-emergency, and Emergency thresholds, respectively. We selected schools within a radius of 800, 1200, 1500, and 2000 m from the monitoring stations. In total, we ran 28 models to estimate whether the results were sensitive to how the $PM_{2.5}$ concentration was measured or the distance from the school to the monitoring stations.

Table 2 shows the results of students who attended schools located within 2000 m to the monitoring stations. In all models, except for the percentage of days classified

Table 1 Descriptive statistics of the dependent and independent variables

Variable	Mean	Std. Dev	Min	Max
Annual GPA	5.91	.54	4	7
Attendance	93.2%	5.6%	15%	100%
Mean $PM_{2.5}$	44.6	16.4	22.2	105.1
% days above WHO threshold	72.9%	11.4%	32.2%	97.3%
% days above EPA threshold	51.7%	16.2%	6.6%	88.9%
% days above MMA threshold	28.4%	17.3%	0%	78.7%
% days above Alert	5.3%	5.6%	0%	20.4%
% days above Pre-emergency	3.0%	4.8%	0%	16.9%
% days above Emergency	1.4%	3.6%	0%	19.1%

Table 2 Effect of air pollution on students' grades from 1st to 8th grade

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Mean $PM_{2.5}$	−0.001***						
% days above WHO		−0.002***					
% days above EPA			−0.001***				
% days above MMA				−0.002***			
% days above Alert					−0.005***		
% days above Pre-emergency						−0.009***	
% days above Emergency							−0.001
Attendance	0.019***	0.019***	0.019***	0.019***	0.019***	0.019***	0.019***
Class							
2nd grade	−0.417***	−0.431***	−0.427***	−0.423***	−0.422***	−0.416***	−0.421***
3rd grade	−0.874***	−0.880***	−0.879***	−0.877***	−0.877***	−0.868***	−0.873***
4th grade	−1.001***	−1.003***	−1.010***	−1.006***	−1.007***	−0.995***	−1.002***
5th grade	−1.349***	−1.342***	−1.346***	−1.350***	−1.352***	−1.349***	−1.349***
6th grade	−1.456***	−1.458***	−1.455***	−1.452***	−1.453***	−1.460***	−1.454***
7th grade	−1.664***	−1.660***	−1.656***	−1.647***	−1.657***	−1.672***	−1.670***
8th grade	−1.486***	−1.484***	−1.482***	−1.479***	−1.481***	−1.484***	−1.490***
Number of students	5,509	5,509	5,509	5,509	5,509	5,509	5,509

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, + $p < 0.10$. Note: Schools are located within 2000 m of the monitoring stations and standard errors are clustered at student level

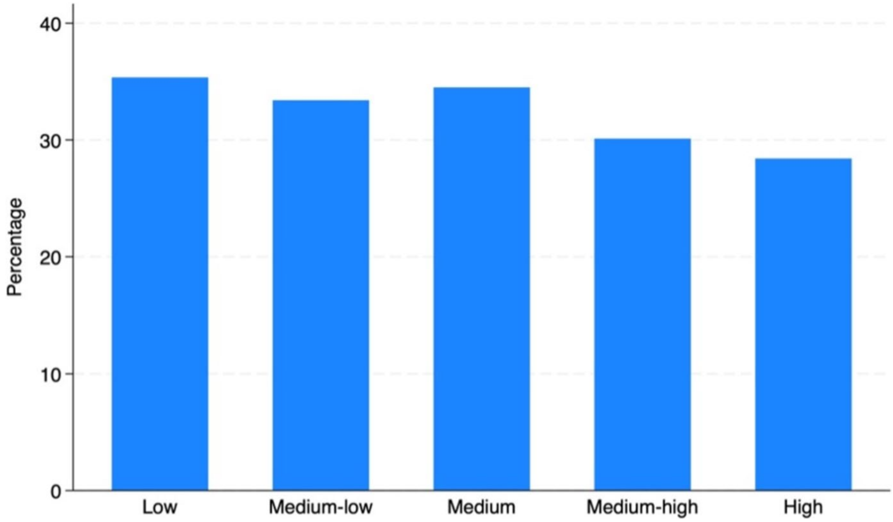

Fig. 1 Percentage of days above MMA standard and schools' SES in 2016

as "emergency," the $PM_{2.5}$ concentration hurt students' GPA, and the coefficients were statistically significant ($p < 0.05$). The outputs show that as the $PM_{2.5}$ concentration increases, its effect also increases. For example, if the percentage of days above the WHO, alert, or pre-emergency threshold increases by one percent, students' GPA decreases by 0.002, 0.005, and 0.009 standard deviations, respectively. However, it is important to note that although the coefficients are statistically significant ($p < 0.05$), the effect sizes are small in the context of most educational research (Kraft, 2020). As expected, there was a positive relationship between attendance and GPA, and the results were consistent across all seven models. As the attendance rate increased by one percent, the students' GPA increased by 0.019 standard deviations ($p < 0.05$). Furthermore, as students progress through school, their GPAs decrease over time; for example, on average, the 8th grade GPA is 1.4 standard deviations lower than the 1st grade (baseline) GPA ($p < 0.05$).

We examined whether the findings varied when we reduced the radius within which schools were included in the sample to 800, 1200, and 1500 m from the monitoring stations, respectively, thereby reducing the sample size of schools and students. The outputs of of Tables A1, A2, and A3 (see Supplementary Materials) show that, independent of the measurement of $PM_{2.5}$, air pollution has a detrimental effect on students' GPA ($p < 0.05$). The results show that as the $PM_{2.5}$ concentration increases, the student's GPA decreases. Furthermore, the attendance ratio positively affected students' GPA; in other words, as the attendance percentage increased, so too did the annual GPA ($p < 0.05$). In brief, the results are consistent and independent of how air pollution is measured and the distance between the student's school and the monitoring stations.

Finally, we explored whether students attending schools in low-income neighborhoods are more exposed to air pollution and whether exposure could impact students differently based on their socioeconomic background. Figure 1 shows the relationship between the percentage of days above the Chilean Ministry of the Environment (MMA) threshold ($PM_{2.5}$ concentrations above 50 μg/m^3) and the SES of the schools participating in the study. The figure suggests that schools enrolling students from low, medium–low, and medium SES are exposed to higher $PM_{2.5}$ concentrations than those from more affluent families. On average, students of low SES have 35% of their school days above the MMA threshold, while those from high SES experience 28% of their school days with $PM_{2.5}$ concentrations above 50 μg/m^3.

To test whether the percentage of days above the Chilean Ministry of the Environment (MMA) affects students differently depending on their family incomes. We ran several fixed effects regression models at the student level using the same strategy presented in Table 2, but we divided our dataset into four subgroups based on students' family income (quartiles). Table 3 presents the main results of the analysis.

The findings show that air pollution affects students from low- and middle-income families (quartiles 1st, 2nd, and 3rd) almost equally. Thus, an increase of one percentage of days with $PM_{2.5}$ concentrations above 50 μg/m^3 reduces students' average GPA by 0.02, 0.03 and 0.02 SD respectively ($p<0.05$). However, there was no statistically significant association between air pollution and students from high-income families.

Discussion

Our findings reveal a statistically significant association between increased exposure to severe air pollution and a decline in students' GPA. The effect of prolonged exposure to fine particulate matter on academic performance is not homogeneous. Students from higher socioeconomic backgrounds demonstrate resilience to the

Table 3 The effect of air pollution on students' grades from 1st to 8th grade by family income

	Income Quartile 1	**Income Quartile 2**	**Income Quartile 3**	**Income Quartile 4**
% days above MMA	−0.002*	−0.003**	−0.002**	0.000
Attendance	0.018***	0.021***	0.018***	0.017***
Class				
2nd grade	−0.535***	−0.465***	−0.440***	−0.321***
3rd grade	−0.963***	−0.949***	−0.938***	−0.731***
4th grade	−1.071***	−1.074***	−1.065***	−0.850***
5th grade	−1.394***	−1.397***	−1.412***	−1.231***
6th grade	−1.482***	−1.499***	−1.551***	−1.291***
7th grade	−1.659***	−1.692***	−1.718***	−1.533***
8th grade	−1.484***	−1.489***	−1.561***	−1.382***
Number of students	1,064	982	1,222	1,373

*** $p<0.001$, ** $p<0.01$, * $p<0.05$, + $p<0.10$. Note: Schools are located within 2000 m of the monitoring stations and standard errors are clustered at student level academic impacts of air pollution, while their lower-income peers experience significant negative effects. The differential influence of air pollution on student achievement underscores the interconnectedness of economic and environmental disparities in the Global South. The results of the analyses conducted for varying distances between students' schools and air quality monitoring stations demonstrate that the main conclusions were robust. Our research findings align closely with previous studies that emphasized the detrimental effects of air pollution on children's academic performance (Berman et al., 2018; Clark-Reyna et al., 2016; Donovan et al., 2020; Gaffron & Niemeier, 2015; Grineski et al., 2016; Kweon et al., 2018; Mizen et al., 2020; Shier et al., 2019; Stingone et al., 2017; Marcotte, 2017). This study contributes to the existing body of longitudinal studies on environmental effects on students' schooling. By focusing on the lasting effects of air quality on academic performance in Chile, our study fills two crucial gaps in scholarly understanding.

First, this study introduces several methodological innovations compared to the previous research conducted in the Latin American context. A pioneering aspect of our study lies in the unprecedented access to longitudinal academic records of a Chilean student cohort spanning their elementary school years. This design offers several key advantages that set our study apart from previous research. By tracking the same students over time, we can more accurately assess the cumulative impact of air pollution on academic performance, rather than capturing a single snapshot in time. This approach allows us to control for individual characteristics and changes that might influence academic outcomes, such as socio-economic status, school environment, or inherent cognitive abilities. The novelty of our dataset lies not only in its longitudinal nature but also in its capacity to link environmental data with detailed academic records, offering a refined understanding of how pollution interacts with various educational contexts. This methodological approach positions our study as one of the first to robustly analyze the long-term effects of environmental pollution on student performance in a non-U.S., non-high-income setting, providing valuable insights that can inform policy decisions in similar contexts. Second, this research extends the geographical scope of this literature to the Global South. From a socioenvironmental perspective, Chile constitutes a paradigmatic case study. Despite its remarkable integration into the global economy and high development indicators, there is a marked socioeconomic inequality manifested in unequal access to essential goods, including clean energy sources. This energy disparity generates heterogeneous patterns of air pollution, which, in turn, exacerbate existing social inequalities through impacts on the academic performance of students from low- and middle-income families. This research suggests that the trends observed are comparable to those found in wealthier nations.

Concerns about environmental justice are raised by this study's findings about unequal exposure to air pollution and its varying effects on vulnerable groups, especially low-income students. Socioeconomic factors often lead to residential segregation, placing lower-income communities closer to polluting sources and exposing students to higher $PM_{2.5}$ levels than the national average captured here. The results of this study indicate that schools with a greater proportion of students from economically disadvantaged families experience a higher frequency of days with poor air quality. Moreover, exposure to $PM_{2.5}$ does not affect the grades of students from high socioeconomic backgrounds, suggesting that the overall air pollution exposure for a child from a disadvantaged family, as measured in this study, may differ from that of a child from a more affluent family, considering factors such as time spent at home, commuting, or in recreational areas. This situation is particularly concerning in the south of Chile. Disadvantaged communities lack access to cleaner heating alternatives, such as natural gas, and experience frequent critical air pollution events, further burdening impoverished neighborhoods (Boso et al., 2022a, 2022b; Pérez-Fargallo et al., 2020; Reyes et al., 2019). The negative association between air pollution and student GPA is especially troubling given the already high average attendance rate (93%). This suggests that, even with consistent attendance, students in polluted areas face additional learning obstacles. Sociological research in southern Chile has further demonstrated this disparity. A recent study found that air quality emergencies lead to increased school absenteeism among children from families with high SES (Hofflinger & Boso, 2021). This finding highlights the unequal ability of families across the socioeconomic spectrum to protect their children from environmental hazards. These factors can exacerbate existing educational inequalities and restrict social mobility among students from disadvantaged backgrounds. Moreover, the negative effects of air pollution extend beyond academic performance, impacting students' long-term health.

Our study has several practical implications from both social and political perspectives. The enduring presence of elevated $PM_{2.5}$ air pollution levels in specific urban hubs in Chile, spanning over decades, juxtaposed against regions characterized by relatively cleaner air, introduces a salient heterogeneity that facilitates analysis of pollution's discernible influence on academic performance. This regional disparity serves as a compelling backdrop for nuanced sociological inquiry into the effects of environmental factors on academic outcomes. The findings also revealed a clear association between schools serving students from lower socioeconomic backgrounds and heightened exposure to $PM_{2.5}$. This documented disparity in air quality exposure shaped by socioeconomic factors underscores the importance of policies rooted in environmental justice principles. Such policies should prioritize mitigating pollution burdens on marginalized communities while fostering equitable access to clean air resources. Therefore, urgent action is warranted, particularly in schools located in polluted environments. Interventions could include upgrading ventilation systems, implementing robust air quality monitoring initiatives, or revising school schedules to minimize exposure during periods of peak pollution. Finally, our research emphasizes the need for stringent air quality regulations in Chile that align with the international standards set by the WHO. Adopting such measures would promote cleaner air for all students nationwide and contribute to leveling the educational playing field, thereby enhancing opportunities for academic achievement across socioeconomic strata.

This study has several limitations. First, there is no information on air pollution inside schools; therefore, we used data from Chile's National Air Quality Information System (SINCA) to estimate the exposure of schools to $PM_{2.5}$ concentrations based on their distance from the air monitoring stations. However, the use of this proxy variable could be problematic because several studies have shown that most air pollution comes from indoor sources (Jorquera et al., 2018), and our study could underestimate the effect of air pollution on students' academic performance. Second, we used students' GPA to measure academic achievement, mainly because we do not have access to standardized tests in elementary and middle school. In Chile, only students in 4th and 8th grades take standardized tests, and during the study period (2009–2016), we only had data available on test scores for 4th graders in 2012. Third, we used air pollution data from cities that have air monitoring stations, which are key components of the Atmospheric Decontamination Plan (ADP). There are several small- and medium-sized cities with high levels of air pollution but without an ADP in southern Chile; therefore, we did not include them in our analysis because of a lack of data. In this sense, we might have underestimated the association between air pollution and students' GPA because we only used cities that have already implemented strategies to reduce $PM_{2.5}$.

Conclusions

This study contributes significantly to understanding the far-reaching social consequences of air pollution, drawing on evidence from Chile—a nation that embodies both the challenges of the Global South and the prosperity seen in more developed regions. Our research sheds light on the disparities in air quality and educational outcomes across different zones within Chile, emphasizing the need to address environmental and educational inequalities not only at a national level but also in a way that considers the diverse realities within countries. Although previous research has documented the health risks associated with children's exposure to air pollution, the impact on educational attainment—a crucial marker of social mobility—has received less attention in the Global South. Our study revealed a robust association between ambient $PM_{2.5}$ levels and student GPA. These findings underscore the latent spillovers arising from regional disparities in access to clean energy sources. The adverse effects on GPA may not only exert enduring influences on the life trajectories of Chilean children but can also reinforce the existing dynamics of unequal development between the metropolitan area and the southern regions. Enhancing ambient air quality in urban centers across Chile yields enduring benefits for children's educational attainment and future career prospects while mitigating environmental injustices. This study underscores the urgent need for stricter air quality regulations that align with international standards. Furthermore, targeted interventions in schools located in polluted areas coupled with community engagement in developing solutions can mitigate the detrimental effects of air pollution on education. Prioritizing clean air for all children in Chile can enhance educational attainment and social mobility, particularly in its less affluent regions, while also serving as a model for other nations with similar disparities. This approach emphasizes the need for targeted interventions that address the unique socio-economic and environmental contexts of regions both within and beyond the Global South, fostering a more just and sustainable future for all.

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Data availability The SIMCE Special License Access Data are nor publicly available because of privacy restrictions, but access can be acquired via the SIMCE data service (https://www.agenciaeducacion.cl/simce/) after application. The recorded air quality data are publicly available via SINCA (https://sinca.mma.gob.cl/#).

Declarations

Conflict of interest The authors declare they have no conflict of interest.

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